EXHIBIT Q

HANDBOOK OF COMPUTER VISION AND APPLICATIONS

Volume 3
Systems and Applications

Bernd Jähne
Horst Haußecker
Peter Geißler

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Editors
Bernd Jähne

Interdisciplinary Center for Scientific Computing
University of Heidelberg, Heidelberg, Germany
and
Scripps Institution of Oceanography
University of California, San Diego

Horst Haußecker
Peter Geißler

Interdisciplinary Center for Scientific Computing
University of Heidelberg, Heidelberg, Germany

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31.4.1 Geometric camera calibration

To obtain quantitative results in digital image processing the geometric camera calibration is an essential part of the measuring procedure and evaluation. Its purpose is to give a relation between the 3-D world coordinate of an object and its 2-D image coordinates. A geometric camera model describes the projection transformation of a 3-D object onto the 2-D CCD sensor of the camera. The quality of the camera calibration is crucial for the accuracy of the stereoscopic reconstruction. Effects not included in the camera model will result in a systematic error.

31.4.2 The camera model

The camera model $\boldsymbol{F}$ is the mathematical description of the relation between the 3-D world coordinates $\boldsymbol{X}$ and the 2-D image coordinates $\boldsymbol{x}$ (see Volume 1, Chapter 17):

$$\boldsymbol{x} = \boldsymbol{F}(\boldsymbol{X}) \tag{31.22}$$

The simplest model is the pinhole camera model. This model is described by four linear transformations including the ten parameters of translation $\boldsymbol{T}$ (3 offsets), rotation $\boldsymbol{M}$ (3 angles), projection $\boldsymbol{P}$ (focal point) and scaling S

$$\boldsymbol{F} = S\boldsymbol{T}\boldsymbol{M}\boldsymbol{P} \tag{31.23}$$

An extended model includes also lens distortion (compare Volume 1, Section 4.5.5 and Chapter 17). Lens distortion is described by a nonlinear correction (see Hartley [26]).

Multimedia geometry. In many applications the camera and the optical system have to be mounted outside the volume of observation. The camera looks, for example, through a glass or Perspex window into the water (see Fig. 31.20). Therefore, a multimedia correction seems to be necessary. The light is refracted according to Snellius' law. Its effect is described by a displacement from the straight line $\Delta X = X_0 - X_{mm}$. If the geometry of the setup is known, ΔX is a function of X_w and of the location of the camera X_k. As this function has no analytical solution, ΔX has to be calculated numerically applying Fermat's principle.

Parameter estimation. The nonlinearity of the camera model does not allow computing the parameters in a direct analytical way. Therefore, a nonlinear minimization method (Levenberg-Marquardt algorithm [18]) is used. The function to minimize is

$$\mathrm{Res} = \sum_i (x_i - \mathbf{F}(X_i))^2 \tag{31.24}$$

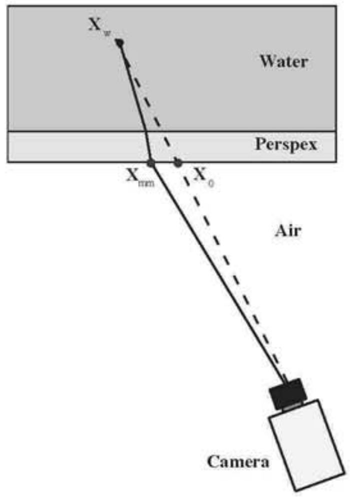

Figure 31.20: *Distortion by multimedia geometry.*

To avoid the algorithm from getting caught in a local minimum, a choice of proper initial values is critical. This can be guaranteed by neglecting the nonlinear part of the camera model (k_1, k_2, p_1, and p_2 set to zero). The parameters of the remaining linear model which are determined by a direct linear transform (DLT) (see Melen [27]), yield the initial values.

Inversion of the camera model. The camera model describes the transformation from world to image coordinates. For the evaluation the inverse relation is of interest—to obtain world coordinates of an object from its position in the 2-D image.

Because the camera model projects a point in 3-D space to a point in a 2-D plane, the solution of the inversion of the camera model is a line. The intersection of the two lines gives the 3-D position of the object (triangulation problem [26]). Mainly due to noise error the lines do not exactly intersect. Therefore, the midpoint of the minimum distance of the two lines is taken as the "intersection point." To invert the camera model a numerical method has to be used because an analytical solution does not exist. For an image point $\boldsymbol{x}$ and a given Z-coordinate Z_0 the world point $\boldsymbol{X}$ to be found is given by the minimum of

$$\epsilon = \left| \boldsymbol{x} - \mathbf{F}(\boldsymbol{X}) \right|_{Z=Z_0} \tag{31.25}$$

As this function is convex, a gradient-based minimization routine always converges.